

ELECTRIC POLARIZATION AND THE VIABILITY OF LIVING SYSTEMS: ION CYCLOTRON RESONANCE-LIKE INTERACTIONS

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Abstract

Wellness can be described in physical terms as a state that is a function of the organism's electric polarization vector $\mathbf{P}(\mathbf{r},t)$. One can alter $\mathbf{P}$ by invasive application of electric fields or by non-invasive external pulsed magnetic fields (PMF) or ion cyclotron resonance (ICR)-like combinations of static and sinusoidal magnetic fields. Changes in human (total) body bioimpedance are significantly altered during exposure to ICR magnetic field combinations. The conductivities of polar amino acids in solution exhibit sharp discontinuities at ICR magnetic fields tuned to the specific charge to mass ratio of the amino acid. It has been reported that protein peptide bonds are broken by such amino acid ICR fields. Remarkably, some of these effects are only found at ultra low AC magnetic intensities, on the order of .05 μT . This is approximately 10^3 below accepted levels determined by engineering estimates. Such strikingly low magnetic intensities imply the existence of physically equivalent endogenous weak electric field oscillations. These observations not only make claims related to electromagnetic pollution more credible but also provide a basis for future electromagnetic applications in medicine. They also reinforce the notion that physical factors acting to influence the electric polarization in living organisms play a key role in biology.

Keywords: Polarization vector, wellness, ion cyclotron resonance, ultra low AC magnetic intensities, bioimpedance, endogenous electric field oscillations

Introduction

We have repeatedly argued (Liboff , 1994;1996;2004a) that the viability of biological systems may be better described in electromagnetic terms as opposed to the prevailing paradigm deeply rooted in biochemistry. There is an excellent case to be made for using an electromagnetic framework to describe the living state. Indeed this may be the only way to explain the huge body of work by Becker, Lund, Athenstaedt, Jaffe, Fukada, Burr, among others, (Liboff, 2004a) all pointing to the expression of highly specific electric field changes associated with development, homeostasis and repair processes.

Consistent with this (Liboff, 2005) is the hypothesis that the electric polarization vector $\mathbf{P}(\mathbf{r},t)$ is the underlying link for this framework. In part this follows from the fact that all of the above experimental observations are either directly or indirectly related to $\mathbf{P}$. The electric polarization also serves as a convenient source density for defining an electric field $\mathbf{\Pi}$ (the Hertz vector) that carries both phylogenetic as well as ontogenic information for the various species. In our view, reduced viability of an organism is characterized by deviations from this intrinsic field. Conversely, the determining factor in the return to wellness is always restoration of the organism's characteristic field, whether by pharmaceutical or electromagnetic therapies, or through intrinsic homeostatic mechanisms such as the immune response. Thus, one can conceive of the often loosely used term wellness as a measure of the living state that can be precisely measured in physical terms.

More recent studies involving time-varying fields have added to this picture, making it apparent that both the static and time-varying characteristics of electric polarization $\mathbf{P}$ are involved in determining the viability of the living state.

Starting with Bassett's work in bone (Bassett et al, 1974), pulsed magnetic fields (PMF) have been widely studied. These are functional because of the internal electric currents induced by external time-varying magnetic fields. A more recent application of Faraday induction, transcranial magnetic stimulation (rTMS) is presently being actively explored for treating various neurological disorders. Similarly, another non-invasive approach, the therapeutic use of ICR (ion cyclotron resonance) magnetic field combinations, following its widespread use in bone repair, has been increasingly studied for its potential use in various medical applications. In this case time-varying magnetic fields are also deployed external to the body. However, in contrast to PMF, the intrinsic therapeutic mechanism does not depend on the emf that is induced, but rather on stimulating specific ions that are tuned to the applied combination of static and sinusoidal magnetic fields. One explanation (McLeod and Liboff, 1986) is that this stimulation enhances membrane transport, thereby signaling changes in cell metabolic activity.

Additional experimental observations further implicate the electric polarization vector. The Seqex device marketed for therapeutic applications measures total body bioimpedance while applying ICR magnetic fields over the entire body. The manufacturer reports that following treatment with this device (total) body impedance is significantly changed at resonance. Most interestingly, there is good evidence (Rossi et al , 2007; Raggi et al, 2009) that these treatments act to reduce free radical body burden. Poggi (private communication) has reported that application of the Seqex magnetic field results in a significant increase of the capacitive reactance in the body. Capacitive reactance (X_c) is defined as $(\omega C)^{-1}$ where ω is the

frequency and C the capacitance. The increase in X_c can be interpreted as due to a reduction of whole body membrane capacitance, presumably the result of either (1) loss of double layer charge density or (2) lowering of the effective dielectric constant.

This observation may be connected to the many earlier experimental reports of ICR-induced physiological effects (Liboff, 2004b) that were likely the result of charge displacement at cell membrane double layers, due to selectively shuttling ions across the double charge layer.

Localizing the electric polarization.

Electric polarization $\mathbf{P}$ is defined as the electric dipole moment per unit volume. For both prokaryotic and eukaryotic organisms, the bulk of the electric dipole distributions are associated with biological membranes, the non-conducting interfaces that separate different compartments of the biosystem. Invariably, the dielectric properties of all biological membranes leading to charge separation on opposite sides of the membrane relate to a limited number of different types of lipid bilayers. The most prominent example is the cell membrane (plasmalemma) separating the interior of the cell (the cytoplasm) from the exterior world (the extracellular matrix). There are other types of biological membranes, notably those within the cell separating the various organelles, such as the nucleus, the Golgi apparatus, the endoplasmic reticulum, and the mitochondria. The mitochondrial walls are especially interesting, since they are made up of two such sets of lipid bilayers. Another unique type of membrane is seen in the oligodendrites, the glial cells in the central nervous system that tend to wrap around nerve cells to provide extraordinary levels of electrical insulation.

Additional examples of charge separation in the living state are found in multicellular ordered sheets of adjacent cells, such as found in the periosteum and in the endosteum in bone as well as similar arrays in other

compartments of each organism, lining the heart, the intestines, etc. Such membrane sheets not only define the organ topologically but also maintain charge separations that are physiologically significant. It is widely assumed that one reason for the large electric field associated with the plasmalemma is to protect the cytoplasmic contents within the cell from random changes in the local electric environment. In very much the same manner one purpose of the membrane sheets is to electrically isolate the interiors of the organs they surround.

Whatever the function of these and other biological membranes they are all intrinsically characterized by their unique ability to maintain high levels of charge separation, i.e. , electric polarization. Therefore when we suggest that the organism's wellness is a function of the electric polarization, we are focusing attention on the organism's complement of membranes.

Biological membranes can be considered as leaky capacitors, with a variety of mechanisms that can enhance the permeability for specific charges or molecules. There is active transport of ions to maintain osmotic equilibrium, different gating mechanisms through channels, binding of molecules to activate signaling, electron/proton transfer during oxidative phosphorylation, and even generation of action potentials in the plane of neural cell membranes. Focusing on biological membranes is hardly a new idea when discussing disease. Indeed, much of modern pharmaceutical medicine involves the control of these leakage mechanisms. We are not suggesting that pharmaceutical solutions to health problems is incorrect, but rather that solutions based in electric polarization may be more complete and ultimately more productive.

It is in this context that ICR phenomena become physiologically important. Properly tuned magnetic field combinations can act to enhance ion transport across membranes in predictable fashion, thus affecting metabolic expression. There is abundant experimental confirmation of this relatively

simple approach to altering electric polarization. However there are serious problems with the theoretical molecular explanations underlying ICR-like interactions. Above all, it is clear that the magnetic field energies involved in these interactions are so small that it seems likely that heretofore unknown physiological processes must play a role.

The electric field at the cell membrane and the kT problem.

To impart information to a biological system, an electromagnetic signal at the least must be distinguishable from the thermal noise background. This requires that the signal provide energy of the order of 0.04 eV or more to the particle involved in the physiological process.

Vincze et al (2008) recently suggested a new approach to explaining the remarkable sensitivities attached to using ICR magnetic field combinations, one that examined in greater detail the effects of the Lorentz force, specifically those affecting ion drift velocity.

Included among the assumptions were a static electric field $\mathbf{E}$, oriented normal to the collinear magnetic fields $\mathbf{B} = B_0(1 + \epsilon e^{i\omega t}) \mathbf{k}$, directed along the z-axis (Fig. 1).

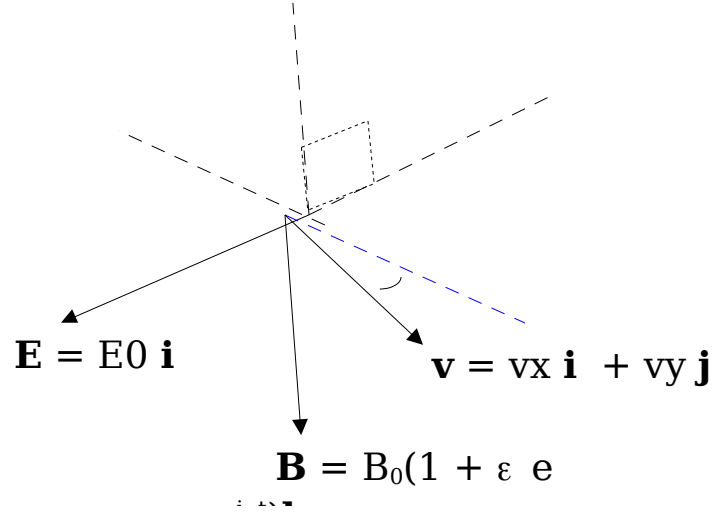


Fig. 1. Fields experienced by a charged particle moving within the xy-plane. The electric field is directed along the x-axis, and the combined AC and DC magnetic fields along the z-axis.

To a first approximation, the ionic drift velocity is

$$\mathbf{v} = \Gamma \frac{J_1^2(\varepsilon\delta)}{2\beta + \frac{\omega^2(\delta-1)^2}{2\beta}} \quad (1)$$

where J_1 is the first order Bessel function whose argument is the dimensionless product $(\varepsilon\delta)$, and where $\delta = \Omega/\omega$, $\varepsilon = B_{AC}/B_0$, $\Gamma = \Omega(E_0/B_0)$, $\beta = 1/2\tau$, and $\Omega = (q/m)B_0$.

The cyclotronic frequency Ω equals the product of the static magnetic field B_0 with q/m , the ratio of charge to mass. The two factors in the Bessel argument are δ , the ratio of cyclotronic frequency to applied frequency, and ε , the ratio of AC magnetic intensity to DC magnetic intensity. Simple collisional damping is assumed, with τ the mean time between collisions.

Apart from the resonant character of the velocity in Eq. 1 the most interesting part of the variation is the Bessel dependence. It is instructive to plot the function $J_1^2(\varepsilon\delta)$, shown in Figure 2, with ε , the ratio of AC intensity

to DC intensity, ranging up to 4 and δ , the ratio of cyclotronic frequency to applied frequency, ranging from 1 (resonance) through 6.

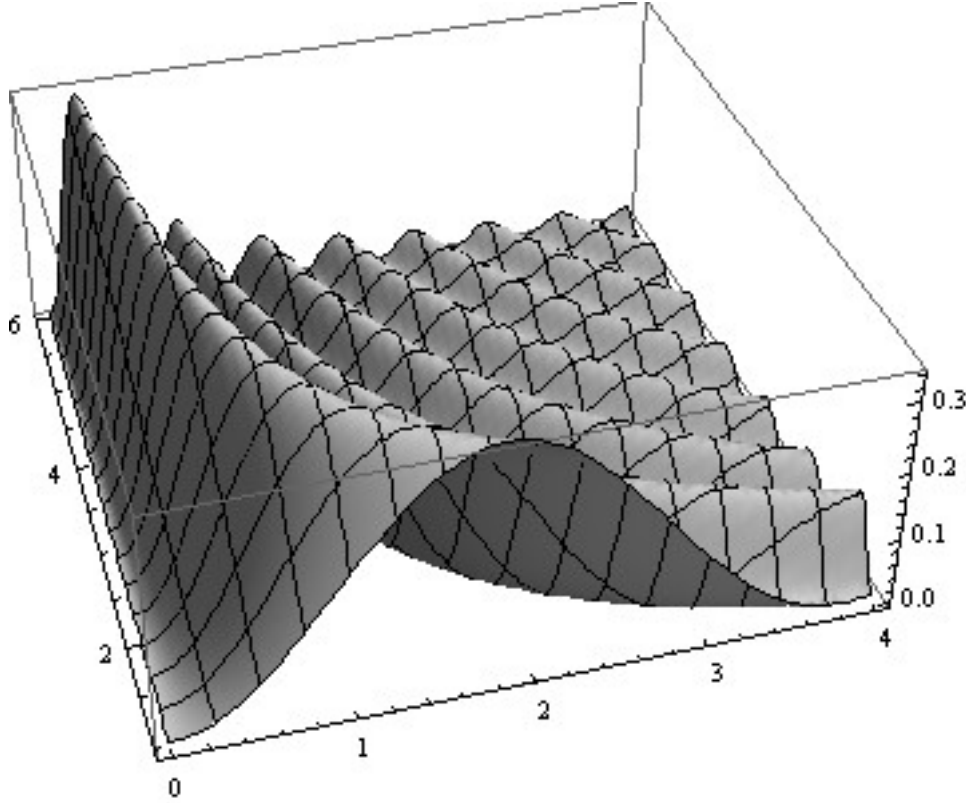


Fig. 2. Plotting the function $J_1^2(\epsilon\delta)$ for the values $\delta = 1$ through 6 and ϵ from 0 to 4.

We find that the peaks in drift velocity can occur for frequencies other than that at resonance, perhaps explaining at least some of the reports indicating weak magnetic field responses at off-resonance frequencies. Also Fig. 2 appears to confirm that at very small AC magnetic intensities the response can be finite but only for very narrow AC windows. This is consistent with the recent reports discussed below, indicating ICR-like biophysical effects at ultra-low AC magnetic intensities.

As to the significance of realizing higher ionic drift velocities under magnetically tuned ion resonance conditions, we speculate that such ions are more likely candidates for capture by channel gating mechanisms.

This solution for the velocity also enables us to avoid the problems with energetics that usually confound the experimental observations of weak ELF biomagnetic interactions.

At cyclotron resonance the ion drift velocity as given in Eq. 1 reduces to

$$v = (q/m) (E_0\tau) J_1^2(\epsilon) \quad (2)$$

which implies that the corresponding kinetic energy is (after assuming $J_1^4(\epsilon) \approx 0.1$)

$$KE = 0.1 (q^2/2m) (E_0\tau)^2 \quad (3)$$

This equals the thermal energy background when $KE = 3kT/2$, where k is Boltzmann's constant and T the absolute temperature. If we substitute $T = 310K$ and the charge to mass ratio for the calcium ion, the following condition is obtained:

$$E_0\tau = 10^{-3} \text{ V/m/s} \quad (4)$$

This criterion, whereby the drift velocity energy equals that of the thermal background, is dependent on the product of local electric field and collision time. For a collision time $\tau \approx 10^{-10} \text{ s}$, this condition is met for ions traveling in electric fields of the order of that found at the cell membrane, namely $E_0 = 10^7 \text{ V/m}$. This implies that biological ions moving under rather weak Lorentz forces nevertheless may be sufficiently accelerated in the vicinity of cell membranes to energetic levels that are comparable to the thermal background in living systems.

Thus it is possible to overcome the so-called kT problem by making use of the high electric field conditions that are present in the vicinity of cell membranes, something that has not heretofore been suggested.

ICR-like Effects at ultra low AC magnetic intensities

Finding a reasonable mechanism at the molecular level to explain ICR-like phenomena has proven to be quite challenging, particularly in view of the very different types of effects that have been observed at resonance over the past twenty years. Initially these effects were grossly physiological: changes in motility in diatoms, growth in plants, learning in rats, proliferation in cells, repair in bone, etc. (Liboff, 2005). However, Zhadin, in a breakthrough experiment (Zhadin et al, 1998) discovered that ICR-like effects also occur in a biochemical context, but only at remarkably small AC magnetic intensities, of the order of $.05 \mu\text{T}$, or approximately a factor of 100 lower than the AC intensities used in all previous ICR studies. This observation, in which the conductivity of polar amino acids in solution is sharply changed under exposure to magnetic field combinations tuned to the exact q/m of the specific amino acid, has been independently replicated in a number of laboratories (Pazur, 2004; Comisso et al, 2005; Giuiliani et al, 2008; Alberto et al, 2008).

Fig. (3) shows striking data from one of these reports (Alberto et al, 2008). The conductivity is plotted against AC magnetic field frequency, with four “typical” runs shown. Discontinuities in conductivity are found, obviously close to the predicted ICR frequencies.

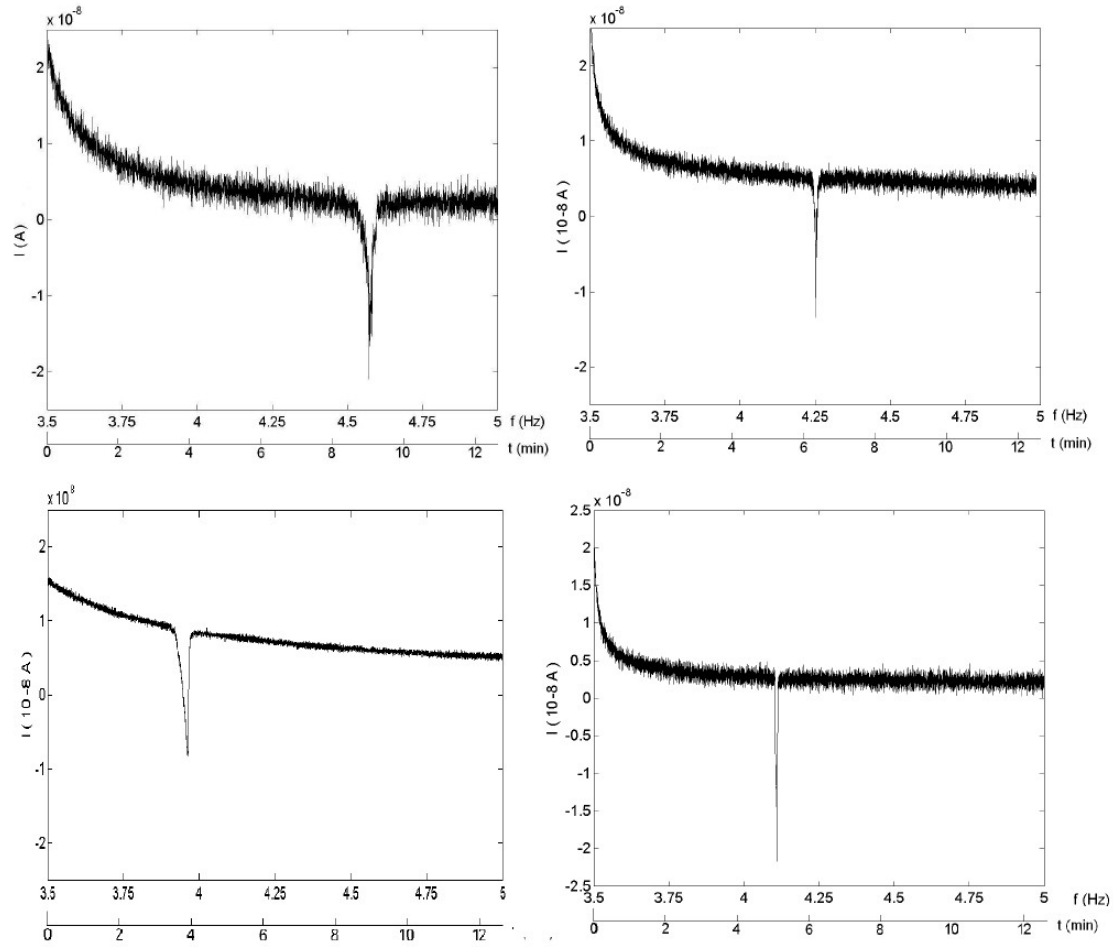


Fig. 3. The conductivity of glutamic acid in solution plotted as a function of magnetic frequency (Alberto et al, 2008). The frequency is ramped at a rate close to 0.1 Hz/min. The authors present four typical runs in order to show the reproducibility of this effect. The four discontinuities occur at slightly different frequencies, with an average deviation of approximately 10%, probably reflecting undetected variations in effective charge or background static field. The frequencies where the discontinuities occur correspond to the ICR tuning condition for the charge to mass ratio for glu^+ . This work is even more remarkable considering that the AC applied magnetic intensity is only .05 μT .

As an extension of Zhadin's discovery Novikov and Fesenko (2001) found an equally interesting effect, namely that peptide bonds in key proteins can be dissolved when exposed to combinations of AC and DC magnetic fields

tuned to amino acid ICR frequencies. This observation is all the more remarkable considering that an ultralow AC magnetic intensity, $.04 \mu\text{T}$, was used, even though peptide bond energies are many orders of magnitude greater than that which might be derived from the energy density of magnetic fields this small. Since this was a cell-free experiment, the energy source for this extraordinary result cannot be in the energies derived from the electric field at the cell membrane.

Resonance Effects in Aqueous Solutions

Note that the ultra low AC observations (Zhadin et al, 1998; Novikov and Fesenko, 2001;

Alberto et al, 2008) in membrane-free solutions are at variance with the changes in capacitive reactance reported by Poggi (private communication), which can be interpreted as decreases in charge density at membrane surfaces. The real significance of the Zhadin experiment may be that it helps reveal the involvement of water in the ICR-like interaction. If application of these tuned fields also affect measurements of ionic conductivity in aqueous solutions, it is reasonable to think that the water/ion interface is an aspect common to both the physiological and the physical observations.

One recent attempt to connect water to ICR was the hypothesis by Del Giudice et al (2002) using quantum electrodynamics to propose the existence of coherent domains in water. But there may be simpler approaches to this question, namely those involving physical chemistry. It is well-known that water enjoys properties that can be thought of as semi crystalline. It has an anomalously high heat of vaporization. Proton conductance can occur along “water wires”, as conveyed by the Grotthus or proton hopping mechanism (Nagle and Morewitz, 1978; Agmon, 1995). There is also evidence (Pomes, 1998) for ionic movement within larger 3-

dimensional stable structures involving hydrogen ions having the form $H_{2n+1}O_n^+$. Aqueous ionic dissociation is always accompanied with hydration layers of the form shown in Fig. 4. The dielectric constant for pure water is extremely large, providing the hypothetical basis for regular structures due to its polarizability in weak electric fields.

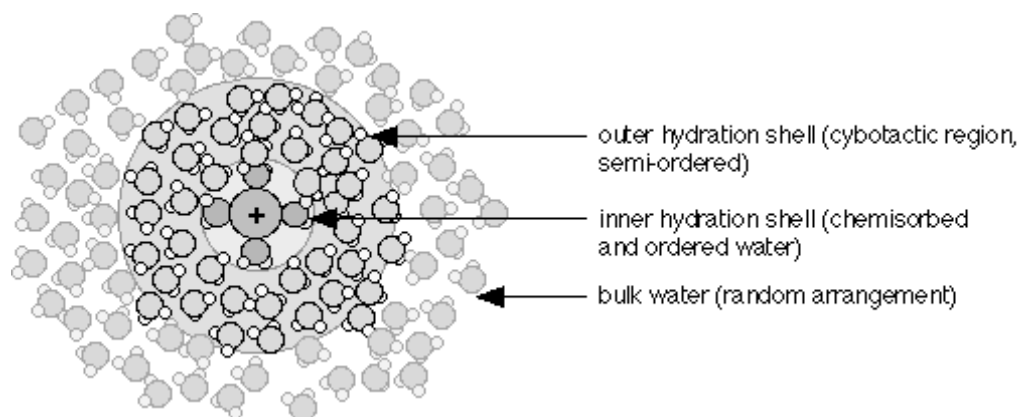


Fig. 4. Solvation shells surrounding a cation. The innermost shell is highly ordered, with the dipole moments of each water molecule symmetrically arranged around the cation. At great distances from the cation, water molecules assume the more random arrangement of bulk water. In between these extremes there is a transition, or cybotactic, zone that is semi-ordered.

Given these tendencies towards organization, it would not be surprising to find collective ordering in water that is dependent on magnetic field/charge interactions. In particular, the static and low-frequency B-field combination is completely pervasive, affecting equally all microscopic regions within the volume of water. Thus whatever the (presently unknown) impact of the tuned Lorentz force on any one ion and its accompanying hydration layer, this change will be precisely the same for all ions within this volume. In effect, the pervasiveness of the field itself dictates the collective response of the water. This pervasiveness in water is less possible for electric fields and/or higher frequency magnetic fields.

Significance of ultra-low AC magnetic biointeraction.

Because ICR-like interactions alter charge densities at membranes and thus affect the electric polarization, there is obvious potential for medical applications, over and above the already accepted use in bone repair. It has previously been observed that a great variety of physiological changes are possible using ICR-like magnetic field combinations. To these we must add the newly discovered effects under ICR tuning that occur at ultralow AC magnetic field intensities.

The original ICR hypothesis (Liboff, 1985) was strongly suggestive of a “natural” role for the earth’s magnetic field (GMF). The term “natural” here refers to the possibility that the changes in physiological expression observed under ICR conditions in the laboratory actually reflect ongoing ICR effects that are evolutionarily conserved. One can ask whether this is still true for these effects at ultralow *magnetic* intensities. In other words where in the environment can one find ELF magnetic periodicities with intensities of the order of $.05 \mu\text{T}$?

We have previously shown (Liboff, 1997) that GMF-related ICR-like “natural” biophenomena may result from the presence of oscillatory electric fields already present within an organism. From a classical standpoint ICR electrodynamics is very similar whether one applies a magnetic oscillation parallel to the static (GMF) field or one applies an oscillatory electric field perpendicular to the static field (E-field ICR). It would not be surprising to find that there exist endogenous low-frequency electric fields that are normal to a component of the GMF that serve the purpose of adjusting the local polarization for whatever physiological outcome is needed.

Accordingly, we speculate that the ultralow B_{AC} intensity windows that have been found to be effective in the experiments by Zhadin and others very likely have their counterpart in equally low internal AC *electric field* oscillations. Thus the interesting questions: Is there evidence of low-

frequency electric field oscillations in the vicinity of cell membranes? And, if such electric fields indeed exist, are the amplitudes of these supposed fields “equivalent” to the .05 μT magnetic intensities reported? That is to say, will the same ICR effects happen if the .05 μT periodic magnetic field that is parallel to the GMF is entirely replaced by a periodic electric field that is perpendicular to the GMF?

One way of dealing with the question of electric field “equivalence” is to assume that the ion velocity is equal approximately to E/B , the ratio of electric field to magnetic field intensities. If we assume that the velocity of a calcium ion is determined by thermal energy considerations, such that $mv^2 = 3kT$, we find that an electric field intensity equal to .02 mV/m is “equivalent” to the magnetic intensity of .05 μT . It is worth noting that electric field changes of this magnitude are readily produced at cell membrane surfaces during processes such as cell ruffling (Cheresh et al, 1999). Such perturbations may be a consequence of the electric field oscillations that are predicted in biological tissues due to coherent effects in the cytoskeleton (Pohl, 1980; Carlier et al, 1987; Pokorny et al, 2005).

Discussion.

We find that ICR-like bioeffects are very dependent on the local electric field in two ways not before suggested. First, the large electric field associated with the membrane may be the source of energy in ICR reactions that helps to provide reasonable signal to noise ratios. Second, small, but periodic changes in the endogenous electric field can serve as a putative interaction model involving the GMF. This interaction can provide a means of using the GMF to regulate physiological function. In both cases, it is clear that electric polarization effects at membranes likely play key roles.

The electric polarization distribution in living organisms result from both genetically predetermined electrogenic sources and externally applied

physical sources. The endogenous factors are principally associated with membrane dipole moments. There are additional specialized contributions by on-board transducers. For example, collagen provides stress-generated potentials to assist in bone remodeling by altering the electric dipole moments at the periosteal and endosteal membranes. In addition to gravitational stresses a variety of external physical factors can alter electric dipole distributions at membranes, such as those associated with the senses.

The pharmaceutical paradigm is based on biochemical preparations acting at the cell membrane. These compounds are universally employed to change specific dipole moments and thus control enzymatic properties in medically useful ways. Similarly, one can apply invasive electric currents to affect local polarization for medical purposes. This was the basis of early protocols to repair non-unions in bone (Lavine et al, 1972). In time this invasive approach gave way (Bassett, 1974) to externally applied time-varying magnetic fields, or PMF (pulsed magnetic fields). A more recent medical application of PMF is seen in the use of transcranial magnetic stimulation (TMS) to treat various neurodegenerative disorders. In both cases, for bone and the brain, the pulsed magnetic field is both large and rapidly changing, enabling Faraday induction of voltages to occur in the nearby tissues of interest. However, because of the wide band of frequencies these pulses contain upon Fourier decomposition, PMF has to be thought of as a “shotgun” approach.

The use of wideband high power PMF for the treatment of bone repair is gradually being replaced by single frequency magnetic field ICR applications that are targeted to specific ions. ICR signals are at the same time both weakly intense and low in frequency, electromagnetic characteristics that make it clear that the efficacy connected to these signals is not dependent on Faraday induction, an interaction that strengthens with higher frequencies and intensities. One can speculate that

the PMF application used in TMS will also eventually be replaced with signal specific ICR magnetic field combinations tuned to the neurodegenerative disorder that is being treated.

Further, it is conceivable that the bulk of the pharmaceutical interventions presently used to tackle medical problems will eventually be replaced by specifically targeted non-invasive magnetic treatments. In general, the use of electromagnetism in treating human illness is more closely attuned to the fundamental character of the living system. If life, at its essence, is an electromagnetic entity, then the problems that are encountered with this construct-disease, trauma, ageing-must also be electromagnetic in origin. It therefore makes sense to look to electromagnetic medicine to deal with human medical problems.

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